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MODELLING OF ABANDONED MINE FLOODING – WATER QUALITY AND TREATMENT REQUIREMENT OVER TIME

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Metal sulphate containing acid mine water decantation is generally expected to be an ever increasing challenge as mining activity winds down on the Witwatersrand. The water is contaminated due to by-products of aerobic bacterial action, which catalyses the oxidation of sulphide minerals in the presence of oxygen and water. During the flooding of an abandoned mine, air is replaced with ground water, limiting the access of oxygen as this gas is only sparingly soluble in water. This paper is a theoretical study on how the quality of decanting mine water at a given location may be expected to vary in the longer term.

Key Words

acid mine drainage, AMD, acid mine decantation, iron oxidising bacteria, mine voids, central rand basin, central basin, model

1 Introduction

The mine voids in the Central Rand Basin beneath the city of Johannesburg, formed due to mining activity, are relentlessly filling up with water. Based on the West Rand Basin, where decanting commenced in 2002, the water is expected to have typical Acid Mine Drainage (AMD) characteristics (Carte Blanche, 2010). The decanting water will have to be treated to remove dissolved metals and acid in order to protect other water resources and the environment.

About 12- to 50Mℓ of AMD decants from the West Rand Basin per day, which is estimated to have a mine void volume of 45million m^3 (Carte Blanche, 2010, miningweekly.com, 2010). For the Central Rand Basin, these figures are 32- to 70Mℓ AMD (estimated) and 400 million m^3 respectively (Carte Blanche, 2010).

The AMD on the West Rand is treated with lime as and when money and reagent is available or left running into the surroundings (Carte Blanche, 2010). In the public domain, most emphasis is understandably placed on the current crises, and no clear picture is presented to the general public what will happen to the AMD over the next several years. The implication is that huge amounts of lime will be required forever.

This paper investigates what could reasonably happen in the next several years by considering the requirements of the bacteria that give rise to AMD, and the changes in their environment due to the cessation of underground mining activity. The study focuses on cases where the mine voids are totally flooded with water.

In the next section, a model is set up to predict the variation in AMD quality over a time period of several decades. Based on this, treatment requirements are established over the

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same time period. The results are then interpreted and suggestions for further work are made at the end of the section and in the conclusions section.

2 Theory and Results

Bacteria such as *Thiobacillusferrooxidans* and *Leptospirillumferrooxidans*, present in water films covering rock surfaces exposed by mining, catalyse the oxidation of pyrite. The bacteria are proposed to do this indirectly by the oxidation of ferrous iron in solution in the presence of dissolved oxygen (Verbaan and Huberts, 1988, Huberts, 1994), which diffuses into the water film from the air that is circulated inside the mine:

$$Fe^{2+}+0.25O_2+H^+\rightarrow Fe^{3+}+0.5H_2O \tag{1}$$

In this process, the bacteria obtain energy for living and multiplying. The ferric iron formed is an oxidising agent for sulphide minerals as follows using pyrite as an example (Huberts, 1994, Moses, Nordstrom, Hermana, and Mills, 1987):

$$FeS_2+14Fe^{3+}+8H_2O\rightarrow 15Fe^{2+}+2SO_4^{2-}+16H^+ \tag{2}$$

This re-generates ferrous ions that are oxidised by bacteria. The net reaction for (1) and (2) is as follows:

$$FeS_2+3.75O_2+0.5H_2O\rightarrow Fe^{3+}+2SO_4^{2-}+H^+ \tag{3}$$
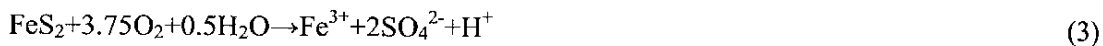
The supply of oxygen in Equation 3 is mainly ensured by ventilation of the mine.

Consider a mine void of $10^6 m^3$. In Johannesburg it contains air at 21% oxygen and a pressure of 0.825atm, and one may use the ideal gas law to obtain the mass of oxygen in the mine void:

$$m=M_r x_{O2}PV/(RT), \tag{4}$$

where Mr is the molecular mass of oxygen ($32gmol^{-1}$), x_{O2} is the mol fraction of Oxygen in air (0.21 for 21%), P is the atmospheric pressure (84 000Pa), R is the universal gas constant ($8.314JK^{-1}mol^{-1}$) and T is the temperature (298K for room temperature). This gives 228ton of oxygen.

If, during the flooding of the mine, all the oxygen in the mine air is used to oxidise pyrite, an iron concentration of at most $0.1g\ell^{-1}$and pH level of 3 is expected to result according to Equation 3. This compares to a value of $0.5g\ell^{-1}$which was measured in West Rand AMD, and implies that most of the oxidation leading to AMD happens before mine closure (assuming that ventilation ceases when operation stops).

Once mine voids are flooded, the oxygen supply used by bacterial action (Equation 1) is limited to the dissolved oxygen in the ground water penetrating the abandoned mine void. The maximum (worst case scenario) concentration of dissolved oxygen in water at 25°C is the value at saturation, $6mg\ell^{-1}$ (Wikipedia, 2010-11-05), which translates into only 6ton of oxygen in the mine void flooded with saturated water compared to 228ton of oxygen of the air-filled void.

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The oxygen availability has therefore been severely restricted on the flooding of the mine void, and now an iron concentration of only $3\text{mg}\ell^{-1}$ and a pH level of 4 can be achieved according to Equation 3. This compares with a maximum standard of $0.3\text{mg}\ell^{-1}$ and pH 5.5-7.5 set for the purification of waste water or effluent (Government Gazette, 1984), so treatment would still be required.

Over a period of time, the AMD in the mine void will therefore be replaced by a water solution that can only contain a maximum of $3\text{mg}\ell^{-1}$ of iron. If one considers a short period of time dt, an iron mass balance (in mg) can be set up as follows:

$$Fe_{out}=Fe_{in}+Fe_{lost}$$

$$CQdt=3\text{mg}\ell^{-1}\times Qdt+1000\ell m^{-3}(CV|_t-CV|_{t+dt})$$

$$C = 3\text{mg}\ell^{-1} - 1000\ell m^{-3}\frac{V}{Q}\frac{dC}{dT} ,$$

(5)

where C is the iron concentration in the AMD ($\text{mg}\ell^{-1}$), Q is the decantation flow-rate (ℓd^{-1}), V is the volume of the mine void (m^3) and t is time (measured in days). Note that the iron concentration in the AMD and the mine void are assumed to be equal – this would therefore give a conservative (high) value of C. Assuming an initial AMD iron concentration of $500\text{mg}\ell^{-1}$, integration of Equation 5 (and leaving out the units) gives

$$C = 3 + 497e^{-0.001(\frac{Q}{V})t}$$

(6)

It can be seen that the concentration of iron in the AMD is a function of Q/V, the decant rate. Using the values for Q and V reported in the introduction, the decant rate for the West Rand Basin, in $\ell d^{-1}m^{-3}$, varies between 0.3 and 1, while that for the Central Rand Basin is expected to be between 0.1 and 0.2. The expected variation in iron concentration in the AMD with time is given in Figure 1 for different decant rates.
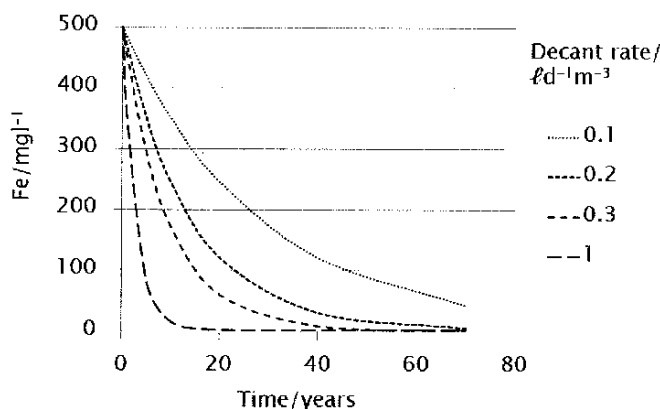

Figure 1. AMD iron concentration variation from a fully flooded mine

For a high decant rate, most of the iron is flushed out of the mine cavity in the first ten years. For lower decant rates, the process is dragged out over a lifetime period.

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The iron and acid in the AMD that resulted from pyrite oxidation would need to be treated, using lime for example. If it is assumed that the iron precipitates out as ferric hydroxide, any iron left in the ferrous state would need to be oxidised in a pre-treatment step and the total equation for neutralisation with lime is as follows:

$$2CaO + FeS_2 + 3.75O_2 + 1.5H_2O \rightarrow Fe(OH)_{3(s)} + 2CaSO_{4(s)} \tag{7}$$
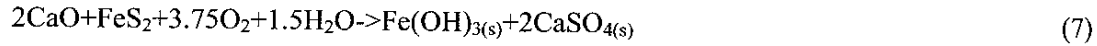
Note that in the left hand side of the equation the oxidation of pyrite using oxygen happens first, and the products are then neutralised by the CaO. The concentration of iron in the AMD, determined by the decant rate, will indicate how much pyrite was oxidised, and the rate of lime consumption can then be calculated using this and the flow-rate of the AMD in conjunction with Equation 7.
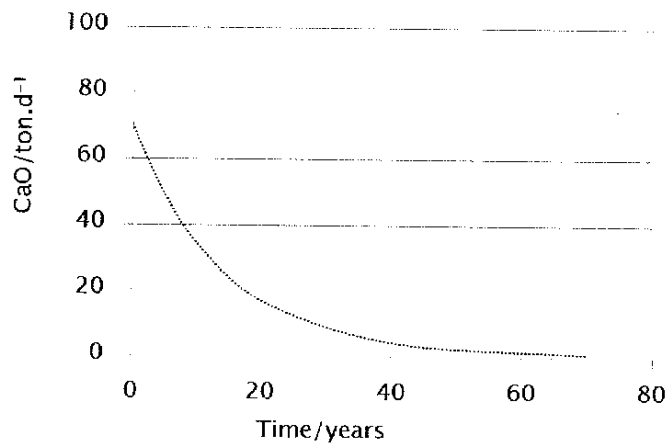
Figure 2. Lime consumption rate for $0.2\ell d^{-1}m^{-3}$ decant rate and $70M\ell d^{-1}$ AMD flow-rate

The consumption of lime will never cease as it is assumed that the ground water seeping into the mine void is saturated with oxygen, and that all oxygen is used to leach pyrite. It can be seen that the consumption of lime can potentially drop to very low levels (bottoming out at about $0.5td^{-1}$), even be it after a couple of decades.

One way of decreasing the consumption rate of lime faster to $0.5td^{-1}$ is to neutralize more timeously and closer to the source of AMD, right in the mine void. CaO as a neutralising agent would probably be unsuitable, as this could cause the water to become basic in mine void pockets where the flooding water is not that acidic. Another option would be ground $CaCO_3$ (marble) which is cheaper and not very soluble in water (Wikepedia, 2010); therefore proposed to be less likely to have a negative effect on the environment:

$$2CaCO_3 + FeS_2 + 3.75O_2 + 1.5H_2O \rightarrow Fe(OH)_{3(s)} + 2CaSO_{4(s)} + 2CO_{2(g)} \tag{8}$$
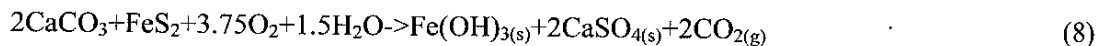
According to Equation 8, one 25kg $CaCO_3$ bag every 4.5m would suffice to neutralise $500mg\ell^{-1}$AMD in a 2m diameter tunnel. Access to place the bags would be problematical once mining activity has ceased, so it may be suggested that the bags be put down as soon as (or even before) a section of the mine has been worked-out and is closed off, as part of the normal mine operations. The neutralization of AMD in this way needs to be investigated

properly before taking the matter further, but if this is possible it would be an effective way of paying dues to the environment.

3. Conclusions

The production of AMD that impacts on the environment seems to start before the sealing of a mine. After the flooding of a mine, bacteria involved in AMD production are denied access to atmospheric oxygen, leading to dramatically decreased oxidation of sulphide minerals surrounding a mine void. As the only source of oxygen is contained in the water seeping into a mine void, the concentration of iron in the AMD will decrease from an initial value (say $500mg\ell^{-1}$) to a maximum of about $3mg\ell^{-1}$ over a period of time, leading to an ever decreasing AMD treatment operating cost.

On the other hand, once a disused mine is flooded, then draining the water again will re-establish the atmospheric supply of oxygen and re-kindle the production of AMD, reversing the trend.

A model was set up assuming that the effluent has the same composition as the solution in the mine void. This could be tested and model parameters could be established using actual data obtained from AMD. The final treatment requirement will depend on the degree of oxygen saturation of the incress.

Current measures for AMD treatment are largely reactive. A prevention strategy, for example by allowing for the (future) in-situ neutralisation of AMD as part of current working mine operations, could be investigated further.

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